A QUALITY ENGINEERING APPROACH TO THE DETERMINATION OF THE SPACE LAUNCH CAPABILITY OF THE PEACEKEEPER ICBM UTILIZING PROBABILISTIC METHODS

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ABSTRACT

This paper outlines the use of a comprehensive and robust methodology for the conceptual design of an expendable launch vehicle employing the existing Peacekeeper ICBM. This methodology includes an Integrated Product and Process Development (IPPD) approach, coupled with response surface techniques and probabilistic assessments. IPPD aids the decision-maker in accurately projecting performance and economic metric values. It also provides a probabilistic framework to address the inherent uncertainty in vehicle requirements in an analytical manner by representing payload, mission, and design requirements as distributions instead of point values. In short, the methodology utilized in this study is a combination of traditional missile and rocket design and quality engineering techniques. The main goal of this method is to design for the most affordable system possible while ensuring technical feasibility and economic viability. This paper shows how these methods were applied to a proof of concept investigation of the space launch vehicle (SLV) capability of the Peacekeeper ICBM.

INTRODUCTION

The continuing use of decommissioned strategic missile systems is a concern for the United States military. The original START II treaty called for the elimination of all multiple-warhead ICBMs. If this treaty or a similar one were ratified, the United States would be required to eliminate all fifty operational Peacekeeper ICBMs, as they are capable of carrying up to twelve independently targeted warheads [1]. However, the Peacekeeper is an important strategic asset with the ability for innovative reuse beyond its original mission. With minimal modifications, the Peacekeeper could be altered to serve as an expendable space launch vehicle for International Space Station (ISS) or other low-earth orbit (LEO) missions.

To address this concern, this study evaluated the SLV capability for the decommissioned Peacekeeper ICBM. The redesigned Peacekeeper will serve as an expendable SLV, delivering a wide variety of payloads. The primary role of this system is to act as a rapid response and emergency re-supply vehicle to the ISS. This mission required a focus on three primary goals: minimization of the time-to-launch, minimization of development and production costs, and the maximization of useable payload.

The first step in the design process was to define the problem by mapping the customer requirements to engineering characteristics. A Quality Function Deployment approach, utilizing a House of Quality, was employed. Possible engine and propellant types, as well as staging arrangements, were organized in a Morphological Matrix of design alternatives. Several vehicle concepts from the Morphological Matrix were then evaluated in terms of performance, cost, availability, reliability, safety, commonality with existing space systems, and compatibility with various launch sites with the use of a Multi-Attribute Decision Making (MADM) technique. A Modeling and Simulation (M&S) environment was created so that the design space could be investigated for technical feasibility. This M&S environment concurrently integrated various disciplines, including propulsion; aerodynamics; flight performance; guidance, navigation, and control (GNC); and structures. Ranges were assigned to several significant design variables, and a sensitivity analysis was performed on the

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responses to see how small perturbations in the design variables would affect the outcome. A parametric study was also performed on some of the assumptions made in the design process so that the exact effects of the estimates on the vehicle concept could be determined. A Response Surface Methodology (RSM) in conjunction with a Monte Carlo simulation was used for these tasks. This methodology was an iterative process and was repeated until both technical feasibility and economic viability were achieved.

METHODOLOGY

Problem Definition

The tool employed in the problem definition stage of this study was the Quality Function Deployment (QFD) process. QFD is a "planning and problem-solving tool that is finding growing acceptance for translating customer requirements into the engineering characteristics of a product [2]." It systematically looks at all of the major elements that go into the product definition. This method creates a high level of customer "buy-in" and group knowledge of the problem.

The first step in defining the problem is brainstorming. Brainstorming is a method for a team to generate creatively and efficiently a high volume of ideas. The brainstorming process first focuses on defining the customer needs and then is used to determine the engineering characteristics, which identify how the customer requirements can be satisfied. Engineering characteristics are a translation of customer needs into product or process attributes. Specifically, they allow the designer to answer the question: "What can be controlled so that the customer's needs are satisfied?"

The broad requirements of the engineering characteristics are then transformed into an interrelationship digraph (ID). The ID (Figure 1) allows the design team to systematically identify, analyze and classify the cause and effect relationships that exist among all critical issues so that key drivers or outcomes can be recognized. As shown, Idea 3 is the main driver, or the issue to address first, of this system, as it affects the remaining three ideas. Idea 1 is the major outcome, as it is affected by Ideas 2-4. This outcome should be the focus for planning as a meaningful measure of success.

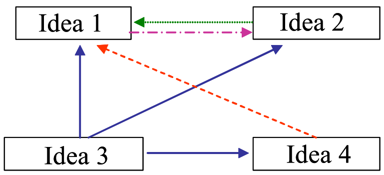

Figure 1: Generic Interrelationship Digraph

Using information generated during the earlier stages of problem definition, a QFD diagram, or a House of Quality, is created. This diagram is a systematic, graphical method that illuminates the most important engineering characteristics in terms of their influence on the customer requirements. The House of Quality is composed of eleven "rooms" (Figure 2).

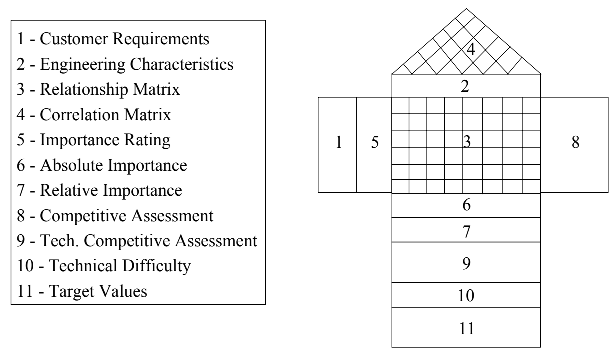

Figure 2: House of Quality Rooms

The first two rooms contain the Customer Requirements and the Engineering Characteristics. The Customer Requirements are frequently referred to as the *whats* of the House of Quality, while the Engineering Characteristics are the *hows*. The engineering characteristics "must not be specific design details or solutions but must be characteristics that can be measured and given target values [2]." It is desirable to label each *how* to indicate a direction of improvement.

The Relationship Matrix room is the body of the QFD diagram. This matrix identifies the correlation between the *hows* and the *whats*. The relationship between these two sets of attributes can be classified as weak, medium, or strong. Each of these relationships is then assigned an associated quantitative value. The goal of this matrix is not to identify a relationship between each and every *how* and *what* but rather to recognize the most important associations. An empty column in the Relationship Matrix indicates that an engineering characteristic previously thought to be significant does not have an impact on any of the customer requirements. This implies that the given engineering characteristic can be eliminated from the House of Quality. More importantly, an empty row shows that a customer requirement is not being properly addressed with the current set of engineering characteristics. Therefore, the design team must identify additional *hows* to satisfy that *what*.

The roof of the House of Quality is called the Correlation Matrix. This room is used to identify the relationships that exist between the engineering characteristics. Analysis of the roof is vital in establishing what trade-offs need to be made. This is important so that possible trades can be recognized early in the design process when the incurred cost is low and changes in the design are made easily. There are four different relationships indicated by the roof: positive, strong positive, negative, and strong negative. The need for a trade-off is demonstrated by a strong negative relationship in the Correlation Matrix.

The Target Values room contains goals set for each engineering characteristic. The design should be evaluated with respect to these targets throughout the design process. The Technical Difficulty shows the ease with which each of engineering characteristics can be achieved using a numerical scale. The assigned values are based on estimates by the design team of the probability of achieving the target values.

The Importance Rating room in the QFD Diagram shows the importance of each customer requirement on a linear numerical scale. The Absolute Importance is obtained by multiplying the quantitative value in each of the cells of the Relationship Matrix by the respective importance rating. These resulting values are then summed for each column in the Relationship Matrix to produce the absolute importance. The Relative Importance is the absolute importance on a normalized scale from 1 to 100. This facilitates the rapid identification of the most significant engineering characteristics for the design problem. In addition, the risk-weighted importances can be determined by multiplying the absolute importance by the technical difficulty ratings.

The Competitive Assessment room shows how the top few competitive products rank with respect to the customer requirements. The Technical Competitive Assessment benchmarks the company performance against the same few competitor products for each of the engineering characteristics. This allows the decision-maker to discern the best places to allocate resources in order to out-perform the competition.

Alternative Concepts Definition

After the completion of the problem definition stage, a potential family of solutions is determined. However, before these alternative concepts can be identified, a full understanding and description of the baseline system is necessary.

Once the baseline is determined, alternative concepts are found through the use of morphological matrices. These matrices allow the designer to visualize all possible technology alternatives for a given engineering characteristic. As shown in Table I, a simplified morphological matrix for an automobile, various technology options for four engineering characteristics are listed. The technology options belonging to the baseline system are circled. The various technology alternatives in this matrix are established through extensive research and brainstorming activities. By choosing a single technology option for each engineering characteristic, an entire system can be defined. For the automobile example, thirty-six possible alternative concepts exist. For a larger system, the potential number of alternative concepts could be too numerous to evaluate. Thus, it is the responsibility of the designer to use engineering expertise to decide which alternatives should be investigated further.

Table I: Generic Morphological Matrix

Engineering Characteristics	*Technology Options*		
Transmission	Automatic	Manual	
Engine	V6	V8	V10
Airbags	Driver-Side	Driver & Passenger-side	
Fuel type	Gasoline	Electric	Hybrid

Alternative Concept Evaluation and Selection

Modeling and Simulation

The next step in this design process includes the creation of a Modeling and Simulation (M&S) environment. The M&S environment usually is based upon the concurrent integration of various disciplines. This environment allows for the investigation of the design space of the selected alternative configurations for technical feasibility and economic viability.

Alternative Concept Downselect

Once the alternative concepts are selected for further study, they are evaluated objectively against each other. This is done to ensure that no alternative concept is eliminated from evaluation too early in the design process. The best alternative for the design mission must be selected and carried through the next stages of the design process. This task is accomplished with the use of a Multi-Attribute Decision-Making (MADM) technique, specifically a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [3].

TOPSIS is a systematic and thorough methodology that describes customer preferences in the form of weights for each criterion. The best alternative has the shortest distance to the positive-ideal solution and furthest distance from negative-ideal solution. TOPSIS "provides a preference order of the deterministic values obtained in the decision matrix, at a given confidence level, resulting in a ranking of the best alternative concept [4]."

First, a decision matrix is created by mapping alternative concepts to evaluation criteria/attributes (customer requirements). The ratings given to the various alternative concepts are either on a quantitative or a qualitative scale. The qualitative criteria are then quantified using an interval scale (very high-9, average-5, very low-1). This attribute value matrix is non-dimensionalized by dividing each quantified design criteria by the Euclidean norm of that metric. In addition, the relative importance (in percent) of each design criteria is determined by dividing each of the customer importance values from the attribute value decision matrix by the summation of all the importance values and then multiplying that by 100%. In order to obtain weighted values for the design criteria, the relative importance for each one is multiplied by the corresponding non-dimensionalized value for each design concept. From this matrix, an ideal positive (A*) and an ideal negative (A^-) solution are determined. For the ideal positive solution, the best value for a given characteristic is taken. This is not necessarily the highest value. For example, it may be desirable to minimize cost; therefore, the best value for cost would be the lowest value. The separation of each alternative from the positive and negative ideal solutions is obtained using the formula below.

$$S_i^{*/-} = \sqrt{\Sigma(AlternativeValue - A^{*/-})^2} \tag{1}$$

The relative closeness of each alternative design concept to the ideal solutions was then calculated using the equation below.

$$C_i = \frac{S_i^-}{S_i^* + S_i^-} \tag{2}$$

The alternative design concept with the highest value of closeness is the highest-ranking alternative.

Design Space Exploration

Once a single concept is selected, it is thoroughly analyzed. This process includes an exploration of the design space around the selected concept. Ranges are assigned to several significant design variables, and a sensitivity analysis can be performed on the responses to see how small perturbations in the design variables affect the desired outcomes. A parametric study also is executed on some of the assumptions made in the design process so that the exact effects of the estimates on the concept can be determined. The goals of design space exploration are to optimize the design and to determine the technical feasibility of the selected concept. In addition, it is important to evaluate the probability of meeting the customer requirements as determined in the problem definition phase of the design process.

Response Surface Methodology

Response Surface Methodology (RSM), based on a design of experiments (DoE), is a multivariate regression technique developed to model the response of a complex system using a single simplified equation [5,6,7]. The responses are modeled using a second order quadratic equation of the form below:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} {x_i}^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon \tag{3}$$

where b_o is the intercept, b_i is the regression coefficient for the linear (first-degree) terms, b_{ii} is the coefficient for the pure quadratic (second-degree) terms, and b_{ij} is the coefficient for the interaction (cross-product) terms. The terms x_i and x_j are representative of the chosen design variables. Epsilon (ε) is the error term which exists because a Response Surface Equation (RSE) is a metamodel and cannot perfectly predict the response. The error term in a “good” RSE usually is insignificant.

The physical creation of the RSE begins with a DoE. A DoE is created based on the number of independent design variables being evaluated. A DoE is a mathematically formulated orthogonal table that, if executed, yields the most information based on a predetermined model with the least number of experiments/simulations. Response surface coefficients and an RSE are created with a central composite or a Box-Behnken DoE. These techniques can be utilized to find the optimal responses within a specified range of the design variables. A statistical analysis software package called JMP [8] is used to create the DoEs.

Responses and design variables are entered into JMP, and a second-order model is chosen. Response surface coefficients and RSEs are then created based on a multivariate regression analysis for each desired response.

A graphical representation of the RSEs are the prediction profilers, a feature within JMP. A prediction profiler (Figure 3) shows the relative impact of the independent design variables on a given response.

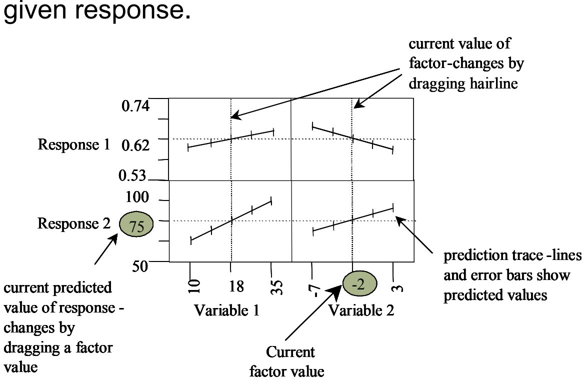

Figure 3: Sample Prediction Profiler [9]

The slope of the curve determines the measure of the impact. A steep slope indicates that a design variable has a significant influence on a given response, while a variable with a shallow slope has little effect on the response. This impact is evaluated within JMP by calculating the partial derivative of one design variable, while keeping the others constant. This shows that the design variables are independent from one another and that their individual impact on the response can be observed.

Another feature of the prediction profiler is the use of hairlines, which enable the user to vary the settings for each design variable. JMP allows movement of this hairline to change a variable's setting within the ranges indicated at the bottom of the profiler on either side of the input variable. The current value of the input is shown between these range values. On the left of the profiler are the responses. Each of these also has a range indicated by the numbers on the top and bottom of each response row. The number in between the range values is the value of the response corresponding to the current variable settings as determined by the hairline placement.

Determination of System Feasibility

Once the responses from the RSEs are collected, the system feasibility needs to be examined. There are three objectives for the determination of the system feasibility phase of the design process. The first goal is to bound and identify the technically feasible design space. The second objective is to identify which constraints are "show-stoppers" or are inhibiting acceptable levels of feasibility. Finally, it is desirable to gain insight into the magnitude and direction of the needed improvements in order to obtain an acceptable feasible design space.

A DoE is merely a subset of the potential number of designs that exist within the given ranges of the problem. Therefore, in order to ascertain the system feasibility, it is necessary to fully explore the remainder of the available design space.

A Monte Carlo simulation [7,10] is used in conjunction with response surface equations in order to model thousands of designs in seconds. The software package Crystal Ball [11] by Decisioneering® is used for this task. Crystal Ball is a risk analysis software package and an add-in to Microsoft Excel. It allows for the definition of design variables as probability functions bounded by a range or a set of values. It then uses the defined ranges in a Monte Carlo simulation. For each uncertain design variable, a probability distribution is used to define the possible values. Distribution types include normal, triangular, uniform, logarithmic, etc.

The Monte Carlo simulation creates Probability Distribution Functions (PDFs) and Cumulative Distribution Functions (CDFs), as shown in Figure 4, in order to illustrate the probability of success for a response. A PDF is the mathematical function that maps the frequency of the response to metrics within the given range. The PDF is then integrated to determine a CDF. The CDF is the mathematical function that maps the probability of obtaining a response to the metric within the given range.

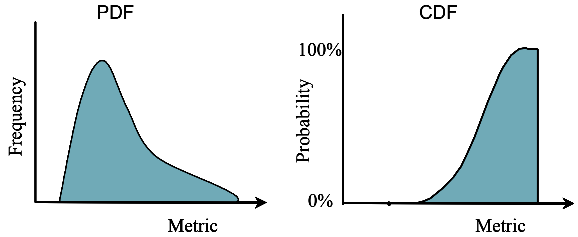

Figure 4: Probability and Cumulative Distribution Functions

If the amount of feasible design space is unacceptable, three options exist for the designer/decisionmaker:

1. Modify the design variable ranges;
2. Relax the constraints;
3. Select a different alternative concept space.

At this point in the design process, it is important to evaluate the system to check if the responses satisfy the customer requirements as established in the problem definition phase. If either the technical feasibility or the economic viability is violated at any point in this iterative process, the design process will be repeated.

APPLICATION OF THE METHODOLOGY

Problem Definition

The intent of this study was to determine the space launch vehicle capability of the decommissioned Peacekeeper ICBM. The design process was based on the primary requirement that the length of time from design to production decision should not exceed eighteen months and that the first Peacekeeper SLV should be operational within two years. The design was to be based on the additional requirements as follows:

- Maximize the payload carried to the ISS.
- Make the payload section compatible with other LEO missions.
- Explore various launch sites and platforms, including Eastern and Western ranges and sea, air, ½ silo and land launches.
- Deliver ten payload sections per year over a period of six years.
- Minimize all associated costs.
- Explore all configuration and propulsion alternatives, including 2+ stages and with or without a post boost propulsion system (PBPS).
- Replace the Advanced Inertial Reference Sphere (AIRS) guidance system and the shroud.
- Maximize technology and components with other military and commercial launch systems.

Customer requirements and importance ratings (Table II) and engineering characteristics with associated directions of improvement and technical difficulty ratings (Table III) were determined through brainstorming sessions and customer interactions.

Table II: Customer Requirements

Payload Delivery	LEO Missions	3
	ISS Missions	5
	Payload Sizing	5
Ranges	Air	2
	Sea	2
	Land	3
Schedule	18 months	5
	10 payloads/yr for 6 years	5
Cost	RDT&E	3
	Operation & Support	5
	Manufacturing	5
System	Availability	3
	Reliability	5
	Commonality	4
	20 year service life	3
Performance	Insertion Accuracy	5
	Orbit	5
Safety	SLV	5
	Personnel/Public	2
	Range Safety	3
	Payload	5
	ISS	5
Other	Environmental Effects	1
	Rollout Time	3

Table III: Engineering Characteristics

Configuration		Propulsion						Structures/Weights								GNC				Safety/Reliability						Operations				
				Propellant Type						Weights			Material Properties								Payload Health			Vehicle						
Number of Stages	Type of Staging	Isp	T/W per stage	Green	High Energy Density	Solid/Liquid	Propellant Cost	Complexity of Layout	Material Cost	Propellant Mass	Initial Mass	Payload Mass	Density	Strength	Heat Resistance	Staging Velocities	Reaction Control System (RCS) Capability	Communication	Controllability	Redundancy	Radiation	Aerothermal Heating	Vibrations	Aerothermal Heating	Vibrations	Facility Compatibility	Turnaround / Launch Time	Payload Preparation Time	Ease of Maintenance/Inspectability	Ease of Propellant Storage
↓	○	↑	↑	↑	↑	○	↓	↓	↓	↓	↓	↑	↓	↑	↑	○	↑	↑	↑	↑	↓	↓	↓	↓	↓	↑	↓	↓	↑	↑
5	3	5	5	3	5	3	3	2	2	4	4	5	3	3	2	2	5	1	5	3	1	1	5	1	5	2	1	2	2	2

The main engineering characteristics were then used to create an ID as seen in Figure 5. Propulsion and configuration are the main drivers of this design while cost is the major outcome.

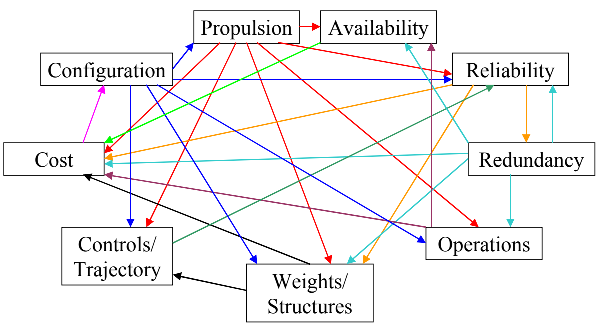

Figure 5: Peacekeeper SLV Interrelationship Digraph

A House of Quality was generated using the customer requirements and engineering characteristics. One of the primary outcomes of this diagram is shown in Table IV, indicating the top six drivers of the design based on the risk-weighted importance ratings.

Table IV: Risk-Weighted Importances

Engineering Characteristic	Risk-Weighted Importance
Controllability	1535
RCS Capability	1065
Number of Stages	965
Propellant Mass	912
Isp	900
Thrust to Weight per stage	900

<u>Alternative Concepts Definition</u>

Two morphological matrices were created for this study. The first (Table V) contained only the propulsion and configuration alternatives, as these were determined to be the main drivers of system. The second contained all alternatives for the subsystems, including those for structures, GNC, range safety, payload delivery, and logistics.

Table V: Morphological Matrix of Propulsion and Configuration Alternatives

	Configuration Alternatives			
Primary Boost	Current 3 stages	Current 3 stages + strap-on 1st stage boosters	Current 3 stages + commercial 4th stage	2 Current stages
Orbit Insertion	Existing PBS	Modified PBS	Small Commercial AKM	Large Commercial AKM
Attitude Control	Existing PBS	Modified PBS - Monopropellant RCS	Modified PBS - Cold Gas	Commercial RCS

* AKM – apogee kick motor PBS – post boost system

Table V resulted in sixty-four possible alternative concepts. From these combinations, seven of the most feasible concepts (Table VI) were selected based on the team's engineering experience and the requirements and constraints provided in the problem definition phase. The remaining subsystems were dependent on the propulsion and configuration and were chosen later in the design process.

Table VI: Seven Alternative Concepts

		Primary Boost	Orbit Insertion	Attitude Control
1	Different PBS Propellant Alternative	3 current stages	Modified PBS	Existing RCS
2	Additional PBS Propellant Alternative	3 current stages	Modified PBS	Modified cold gas RCS
3	Small Commercial AKM Alternative	3 current stages	Small AKM	Commercial RCS
4	Strap-On Boosters Alternative	3 current stages with strap-ons	Existing PBS	Existing RCS
5	Large Commercial AKM Alternative	2 current stages	Large AKM	Commercial RCS
6	Small AKM and Boosters Alternative	3 current stages with strap-ons	Commercial AKM	Commercial RCS
7	Monopropellant PBS Alternative	3 current stages	New PBS	New Monopropellant RCS

Alternative Concept Evaluation and Selection

Modeling and Simulation

In order to evaluate the seven alternative concepts, a modeling and simulation environment was created. Analysis tools for propulsion, aerodynamics, structures, GNC, flight performance, cost, and logistics were integrated to assess the overall performance of each of the alternatives.

The primary calculations for the propulsion analysis of selected alternatives were based on the fundamental rocket equation for two body orbital mechanics. Using this equation and information about each Peacekeeper stage, the ΔV and payload capabilities of each alternative was modeled. The ΔV available from each stage was compared to a calculated value of ΔV (based on a Hohmann transfer assumption) required to reach the ISS. From this, the payload mass was iterated to determine the maximum payload mass while still allowing for a successful transfer.

A custom aerodynamic analysis tool was developed in MATLAB in order to estimate the drag on the vehicle during ascent based on the equations in Fleeman [12].

The GNC system was analyzed by evaluating off-the-shelf technologies for a space launch vehicle. A thorough analysis of the different off-the-shelf technologies was performed so that the team could reduce the GNC weight but also provide the vehicle with an acceptable level of guidance accuracy. In addition, the reaction control thrusters were sized according to the customer requirements in order to achieve the rotation and translation time requirements. The output was the mass of the reaction controls in terms of engine mass, mass of the required tanks, and propellant mass.

A preliminary trajectory and orbit transfer analysis tool was developed to simulate the trajectory that the Peacekeeper SLV would follow when launched from Earth to a circular low-Earth parking orbit, and to simulate the orbit transfer from the parking orbit to the destination orbit (ISS or LEO).

Optimal Trajectories by Implicit Simulation (OTIS) served as a trajectory confirmation tool for the redesigned Peacekeeper SLV, in addition to providing a value for the useable payload that could be placed in a predefined orbit.

The cost and logistics analysis was performed by examining the logistics of the system and the life cycle costs through the use of historical data of similar space launch systems and ICBM programs.

Alternative Concept Downselect

The seven alternative concepts were evaluated against each other in TOPSIS based on the results obtained in the M&S environment, using the customer requirements and the top risk-weighted engineering characteristics as the design criteria. The Strap-On Boosters Alternative was the closest to the ideal solution in the TOPSIS methodology. The main advantage of the Strap-On Boosters Alternative was an above average useable payload capability. In addition, this alternative used as much of the existing Peacekeeper ICBM as possible with minimal costs.

Recall, however, that only seven alternatives of a possible sixty-four were evaluated. Because of this, the Strap-On Boosters Alternative was examined more carefully in order to determine if it could be improved upon. One area for potential improvement was the reaction control system. The Strap-On Boosters Alternative used bipropellants for its fuel and oxidizer. It was decided that the best option for the reaction control system instead would be a cold gas system powered by helium. The cold gas alternative presents many advantages, as it is safe, nontoxic and simple to design and maintain. With this modification, the final configuration consisted of the existing first three stages of the Peacekeeper ICBM with the addition of two Castor IVA strap-on boosters and a replacement cold-gas RCS on the fourth stage.

Design Space Exploration

The detailed concept refinement of the selected final configuration is presented in Reference [13]. The design space exploration is based on the results from that concept refinement.

The design space exploration methodology was used in conjunction with OTIS. During the conceptual phase of design, certain design parameters had a range of possible points rather than a single fixed value. In order to evaluate the effect of each of these parameters on the maximum useable payload weight, it was necessary to investigate the design space around these variables. In order to model this, a DoE was run in OTIS for a range of settings for six different design variables. These six variables were the structural mass of the fourth stage, the shroud mass, the I_{sp} and mass of propellant of the fourth stage, as well as the ISS orbit and a drag factor. The drag factor was simply a multiplier by which the baseline drag of the vehicle was increased.

The six variables selected were only a small sampling of the number of design parameters that can be evaluated with a DoE, but there are a number of reasons why this group was chosen. The first was a limit on the number of runs necessary to perform the DoE. Using a central composite design, forty-five runs of OTIS were needed to determine the effects of just these six variables. Each run of OTIS is time consuming, not just in the time it actually takes for the optimization to occur but also in the setup of the appropriate inputs. Unlike many other analysis codes, each run of OTIS must be done by hand due to the sensitivities of the optimizer. Therefore, the forty-five runs could not be set up to run automatically but were evaluated by modifying the OTIS inputs manually. Secondly, it was desirable to concentrate on the effects of the limited variables that would be affected by the modification to the system to create the Peacekeeper SLV.

The results from this DoE are shown in the prediction profiler in Figure 6. As mentioned earlier, the slopes of each line show the effect on the useable payload due to each design variable. The ISS orbit showed almost no impact on the amount of payload. This design parameter was allowed to vary between the perigee and apogee heights of the ISS, in order to determine the effects of where the Peacekeeper SLV actually docks with the ISS. Similarly, the I_{sp} and mass of propellant of the fourth stage had little effect on the amount of payload. These two variables showed the expected trend of increasing payload as the I_{sp} and amount of propellant were increased, but their effect was minimal. This result could have an important influence on any decisions to modify the existing fourth stage to increase performance. While it would be technically feasible to increase the mass of propellant and change the ratio of fuel to oxidizer to increase I_{sp}, the results shown here indicate the additional costs necessary to do this far outweigh the potential benefits. Similarly, the drag factor did not have as much of an impact on useable payload as had been expected. Although the maximum payload did decrease as the drag factor was increased, this change was not a large one. A factor of 1.5 times the baseline drag, only led to a payload reduction of approximately 500 pounds.

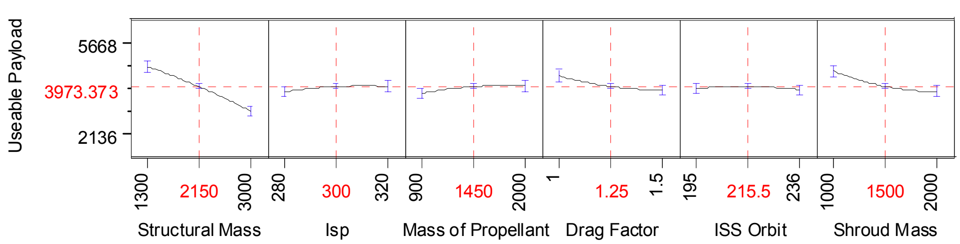

Figure 6: Effect of Design Parameters on Useable Payload

The two design variables that had the most dramatic effect on useable payload were the structural mass above the third stage and the mass of the shroud. Figure 6 indicates that structural mass had almost a one-to-one relationship with the amount of useable payload. Therefore, although the Peacekeeper SLV would place the same amount of mass into ISS orbit, if the structural mass were reduced, the amount of useable payload could be increased. A similar trend existed for the shroud mass. In this case the effect was not as pronounced because the shroud was released at the same time as third stage ignition so it was not carried for the entire mission. Simply based on this small DoE, the driver of this SLV design is obvious. The goal of the designer should be to constantly reduce weight.

Determination of System Feasibility

The design space exploration in OTIS also produced an expected estimate of the amount of useable payload. Using the RSEs integrated with Crystal Ball, input ranges were established for each of the six parameters. The minimum and maximum values for each of these parameters are shown in Table VII.

Table VII: OTIS Design Variable Ranges

Design Variable	Min	Max	Units
Structural Mass above 3rd Stage	1300	3000	pounds
Isp of the 4th Stage	280	320	seconds
Propellant Mass of 4th Stage	900	2000	pounds
Drag Factor	1	1.5	--
ISS Orbit	195	236	nautical miles
Shroud Mass	1000	2000	pounds

Each of the design variables, except the drag factor, was input as a uniform distribution. This meant that any point between the minimum and maximum values had an equally likely chance of being selected. In the case of the drag factor a triangular distribution, with a most likely value of 1.25, was used. The cumulative distribution function for maximum useable payload weight that resulted from Crystal Ball is shown in Figure 7.

There is a ninety percent (90%) probability that the Peacekeeper SLV will be able to transport at least 3,162 pounds of payload to the ISS. Similarly, there is a ten percent (10%) chance that as much as 4,668 pounds of useable payload could be carried.

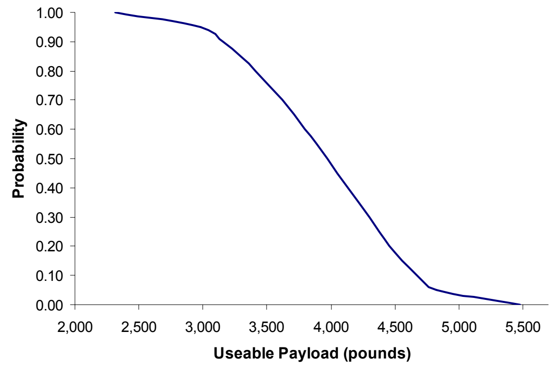

Figure 7: Estimation of Useable Payload to the ISS

CONCLUSION

This paper described a technique in which a structured and robust methodology was applied to the conceptual design of a ballistic missile system. This methodology provided an organized approach to the fundamental phase of problem definition through the use of Quality Function Deployment. A family of alternative solutions was created and analyzed in a multi-disciplinary, integrated modeling and simulation environment. Due to the complex nature of this problem, a Multi-Attribute Decision Making tool allowed for the comparison between the alternatives based on a wide range of performance and economic criteria. Finally, using a Monte Carlo simulation in conjunction with a Response Surface Methodology, the uncertainty was quantified so that technical feasibility and economic viability could be assessed early in the design process. This study demonstrated the application of this quality engineering approach to the design of the Peacekeeper SLV.

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REFERENCES

1. *Peacekeeper Weapon System Baseline Configuration Description*. Directorate of Engineering. Ballistic Missile Office. USAF Systems Command. USAF. March 1985.
2. Dieter, George E., Engineering Design: A Materials and Processing Approach, McGraw-Hill Companies, Inc., New York, 2000.
3. Hwand, C.-R., Yoon, K., Lecture Notes in Economics and Mathematical Systems, Springer-Verlag Berlin Heidelberg, New York, 1981.
4. Kirby, Michelle and Mavris, Dimitri, "A Method for Technology Selection based on Benefit, Available Schedule and Budget Resources", AIAA, 2000 World Aviation Conference, October 10-12, 2000.
5. Box, G.E.P., Draper, M.R., Empirical Model Building and Response Surfaces, John Wiley & Sons, New York, 1987.
6. Montgomery, D.C., Design and Analysis of Experiments. 3rd Edition., John Wiley & Sons, New York, 1991.
7. Mavris, D.N., Bandte, O., Schrage, D.P., "Application of Probabilistic Methods for the Determination of an Economically Robust HSCT Configuration", AIAA 96-4090.
8. SAS Institute Inc., JMP, Computer Program and User Manual, Cary, NC, 1994.
9. Kirby, M.R., Mavris, D.N., "An Approach for the Intelligent Assessment of Future Technology Portfolios", AIAA 2002-0515.
10. Mavris, D.N., Bandte, O., "Economic Uncertainty Assessment Using a Combined Design of Experiments/Monte Carlo Simulation Approach with Application to an HSCT", 17th ISPA Conference, San Diego, CA, May 1995.
11. Decisioneering, Inc., Crystal Ball, Computer Program and User's Guide, Denver, Co., 1993.
12. Fleeman, Eugene L. Tactical Missile Design. AIAA Education Series, AIAA, 2001.
13. Kumpel, A.E., Barros, P.A., Burg, C.M., Villeneuve, F., Mavris, D.N., "A Conceptual Design for the Space Launch Capability of the Decommissioned Peacekeeper ICBM", AIAA-2002-5854.